Physical and Interdisciplinary Regional Ocean Dynamics and Modeling Systems

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LONG-TERM GOALS

This research is concerned with the understanding and modeling of physical and interdisciplinary regional ocean dynamics, including the development of new mathematical and computational methods and systems for ocean dynamics and predictions. The general focus is littoral ocean processes and their interactions with the deep ocean, with the intent to utilize acoustical-physical-biogeochemical measurements to enhance predictive capabilities and contribute to efficient real-time at-sea research experiments, naval operations and coastal seas management.

OBJECTIVES

General objectives are to:

i)   Analyze and study regional physical and physical-acoustical-biogeochemical dynamics,

ii) Quantify regional predictabilities and improve error, probability and uncertainty modeling and predictions, and,

iii) Evolve concepts and determine methodologies for regional adaptive modeling and adaptive sampling with the intent to increase predictive capabilities.

For each objective, a specific emphasis is on acoustical-physical interactions and the use of acoustical-physical measurements. There is a generic applicability to these objectives. For efficient progress, focus is on specific regions: Monterey Bay and the California Current System (CCS); Chinese shelf waters and the East and South China Seas; the eastern Mediterranean Sea, especially the Levantine Sea; and the Mid-Atlantic Bight (MAB) and northwest Atlantic ocean, in particular Massachusetts Bay (Mass. Bay) and the New England shelf region (from Long Island Sound to the Gulf of Maine, including the shelfbreak and continental slope).

APPROACH

The technical approach is based on the comparison and optimal combination of measurements and models via data assimilation, including the development of adaptive modeling and adaptive sampling schemes. The main uncertainty prediction and assimilation scheme is Error Subspace Statistical Estimation (ESSE). The methodological research is organized as:

1. Interdisciplinary Modeling, Data Assimilation and Parameter Estimation via ESSE

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2. Uncertainty Models and Parameterizations

3. Skill Metrics and Predictability Limits

4. Towards Adaptive Modeling and Distributed Expert Systems

The ongoing physical, acoustical and biogeochemical applications and scientific research focus on the:

1. Dynamics of Frontal Systems and Coastal-Deep Seas Interactions (MAB and Shelfbreak Front, East and South China Seas)

2. Dynamics of Coastal Bays and Shelf Interactions (Monterey Bay/CCS, Massachusetts Bay/New England shelf).

3. Dynamics of Semi-Enclosed Seas and Water-Mass Interactions (Mediterranean Sea regions)
4.
Several contributions are linked to ONR collaborative projects.

WORK COMPLETED

Methodological Research

1. Interdisciplinary Modeling, Data Assimilation and Parameter Estimation via ESSE

For the MB06 and SW06-AWACS exercises, a new free-surface version of the HOPS modeling system with a 2-way nesting and Grid computing capability was developed with the Harvard group. To account for the free-surface, new algorithms were developed and implemented for the: open-ocean boundary conditions; 2-way nesting algorithms; initialization procedures and optimal interpolation schemes. Manuscripts are in preparation.

Adaptable components of the ESSE system were reviewed, discussed and illustrated (Lermusiaux, 2006b). These components include error estimates (initial, prior and posterior covariance re-scaling, models of truncated errors, etc), ensemble sizes, error subspace ranks, covariance tapering by Schur product and parameters of stochastic error models. Illustrations were provided for influences of the ensemble size, error subspace rank, covariance tapering and stochastic forcing.

Adaptive sampling approaches and schemes were also outlined and their capabilities illustrated (Lermusiaux, 2006b). The simplest scheme is heuristic, selecting the sampling manually based on predictions and experience. The other new schemes are quantitative. Adaptive sampling via ESSE selects the optimal sampling plan out of a set of candidates, dynamically predicting the impact of measured data on future and past ocean estimates. The other schemes, developed in collaboration with MIT-OE and OASIS, compute the optimum sampling path approximating the impact of measured data and usually assuming a fixed objective. One scheme is based on mixed-integer-programming commercial software to solve the optimization problem. The other is based on genetic algorithms. They are described and illustrated by Yilmaz et al (2006a, 2006b) and Heaney et al (2006).

A report on the Progress and Prospects of U.S. Data Assimilation in Ocean Research was written and accepted (Lermusiaux et al, 2006b).

2. Uncertainty Models and Parameterizations

Scientific computations for the quantification, estimation and prediction of uncertainties for ocean dynamics were reviewed, developed and exemplified (Lermusiaux, 2006a). Challenges involved in realistic data-driven simulations of uncertainties for four-dimensional interdisciplinary ocean processes were emphasized. Equations governing uncertainties in the Bayesian probabilistic sense were summarized. A new stochastic-deterministic ocean model was presented and utilized.
The use of Principal Orthogonal Decomposition (POD) for faster field uncertainty calculations and predictions continues to be investigated, in collaboration with Brown U.

3. Skill Metrics and Predictability Limits

A large number of data-model comparisons were carried out before and after the MB06 and SW06-AWACS exercises. The skill of the new free-surface, 2-way nested, tidally forced Harvard modeling system was evaluated, by quick-look and quantitative comparisons to data from ships, gliders, AUVs and remote (satellite and CODAR) platforms. Sensitivity studies to a large set of parameters were also carried out in real-time, in both regions. Uncertainties of Lagrangian Coherent Structures were computed (Lermusiaux et al, 2006a) and software that links HOPS/ESSE to ManGen further improved, with potential for new feature-based skill metrics.
A manuscript on the evaluation of skill metrics and use of new model training schemes for MREA exercises in the Mediterranean is completed, in collaboration with the HU team (Leslie et al, 2006).

4. Towards Adaptive Modeling and Distributed Expert Systems

Novel adaptive modeling approaches based on simplified maximum likelihood principles were developed and applied to physical and physical-biogeochemical dynamics (Lermusiaux, 2006b).
New matlab software implemented at HU was utilized for the high-resolution inverse modeling of barotropic tides in various ocean regions.
The first version of a web-enabled configuration and automated control software was published (Evangelinos et al, 2006).

A post-doc (N. Yilmaz, for 3 months) and a PhD student (D. Wang, MIT-OE) were advised officially.

Applications and Scientific Research

1. Dynamics of Frontal Systems and Coastal-Deep Seas Interactions

MAB and Shelfbreak Front. Acoustical-Physical uncertainties were computed and studied based on HOPS and ESSE for the PRIMER experiment (Lermusiaux, 2006a; Lermusiaux et al, 2006a). During the SW06-AWACS exercises, data-driven ocean simulations were transferred to K. Heaney, T. Duda and G. Gawarkiewicz for adaptive sampling and oceanographic studies. Collaborations are ongoing.

2. Dynamics of Coastal Bays and Shelf Interactions

Mass Bay: The spatial variability of biological probability densities was computed and evaluated (Lermusiaux et al, 2006a).

Monterey Bay/*CCS.* Physical dynamics studies are carried out. HOPS fields for the 2003 and 2006 exercises were transferred to B. Cornuelle. He is initializing the hydrostatic and non-hydrostatic versions of the MIT-gcm with these fields, so as to carry out model and dynamics comparisons.

3. Dynamics of Semi-Enclosed Seas/Regions and Water-Mass Interactions

A manuscript is prepared with G. Cosarini (U. Trieste) on our results on the use of ESSE to assimilate water quality data in a 3d ecosystem model of the lagoon of Venice and study the corresponding dynamics at seasonal scales. The sensitivity to initial and boundary conditions were estimated and biogeochemical data assimilated. An updated assessment of the water quality was obtained.
A manuscript describing our physical-acoustical modeling and adaptive sampling research for the Focused Acoustic Forecasting-05 field exercise (www.deas.harvard.edu/~leslie/FAF05) that occurred around the islands of Pianosa and Elba in the western Mediterranean in July 2005 has been published (Wang et al, 2006). Another one is being prepared on Adaptive Rapid Environmental Assessment.

RESULTS

Methodological Research

1. Interdisciplinary Modeling, Data Assimilation and Parameter Estimation via ESSE

Adaptable components of the ESSE system were illustrated (Lermusiaux, 2006b). Results indicate that error estimates, ensemble sizes, error subspace ranks, covariance tapering and stochastic error models can be calibrated by such quantitative adaptation.

In the Pt Ano Nuevo and New England shelfbreak front regions, we found that accurate larger-scale initial conditions, tidal forcing and atmospheric (wind) forcing are essential to predict high-resolution dynamics on the Ano Nuevo shelf and near the shefbreak front, respectively. Ocean process studies in the 2-way nested domains (0.5–1.5km and 1–3km, respectively) are underway.

New adaptive sampling schemes described in (Lermusiaux, 2006b; Heaney, 2006; Yilmaz et al, 2006a, 2006b; Wang et al, 2006) can be used in real-time with the potential for efficient sampling.

2. Uncertainty Models and Parameterizations

Capabilities of the stochastic-deterministic primitive-equations were illustrated in three data-assimilative applications (Lermusiaux, 2006a): estimation of uncertainties for physical-biogeochemical fields, transfers of ocean physics uncertainties to acoustics, and real-time stochastic ensemble predictions with assimilation of a wide range of data types. Relationships with other modern uncertainty quantification schemes and promising research directions were outlined.

3. Skill Metrics and Predictability Limits

A manuscript was completed for MREA (Leslie et al, 2006). Another one is being prepared on the uncertainties and predictability of Lagrangian Coherent Structures estimated using HOPS-ESSE-ManGen. The focus is on two upwelling events and one relaxation event in the Monterey Bay region.

4. *Towards Adaptive Modeling and Distributed Expert Systems*

In our regional adaptive modeling studies (Lermusiaux 2006b), model parameter values and model structures were jointly calibrated to ocean data. The adaptive schemes are for now simple. They are based on an ensemble of simulations using different model structures and parameter values, and on the automated selection of the model version with the best predictive skill. For physical adaptive modeling, predictive skill was measured by the bias, root-mean-square-error and pattern correlation coefficient of model estimates. A manuscript has been published on our web-enabled configuration and automated control software (Evangelinos et al, 2006).

Applications and Scientific Research

1. *Dynamics of Frontal Systems and Coastal-Deep Seas Interactions*

It was found that sub-grid-scales and sub-mesoscale variability can be statistically depicted by stochastic terms in the CCS-Monterey Bay and New England shelfbreak front regions (Lermusiaux, 2006a, Lermusiaux et al, 2006a). Transfer of un-resolved energies to resolved deterministic dynamical uncertainties occurs. Differences in the vertical show effects of the vertically-varying amplitudes of the stochastic forcings, computed based on data misfits and geostrophic balance. Temperature and salinity uncertainties are concentrated around the thermocline and halocline while velocity uncertainties are more slowly decaying in the upper 200m depth. Plans to study the impact of strong storms on the shelbreak front, as observed in 1996 and 2006 are being outlined with G. Gawarkiewicz.

2. *Dynamics of Coastal Bays and Shelf Interactions*

Mass Bay: Because of the limited biological data at the end of September 1998, biological covariances and uncertainty fields were found closely linked to the dominant biological dynamics (Lermusiaux, 2006a; Lermusiaux et al, 2006a). For Chl, uncertainties were largest above Stellwagen Bank, near its sub-surface maxima. Detritus uncertainties were also large on the northern side of the Bay near Cape Ann due to detritus sinking and to downwelling. For nitrate, it was largest just below the largest Chl uncertainties and along the coast at depth due to upwelling.

Monterey Bay/*CCS*: A manuscript describing ESSE error and ocean fields for Monterey Bay is being prepared. It includes stages of the upwelling and relaxation states, establishment of a cyclonic circulation in the Bay during upwelling conditions, diurnal scales and topography-induced small scales. Volume term-by-term and flux balances are being computed for the 2006 MB06 data.

Impacts of tidal processes are significant on the Pt Ano Nuevo shelf. They are being studied.

3. *Dynamics of Semi-Enclosed Seas/Regions and Water-Mass Interactions*

With G. Cosarini (manuscript in preparation), using ESSE, the importance of various inlets and nutrient loadings in the Lagoon of Venice was found to be seasonally variable and the assimilation of water quality data better assessed the water quality in the region.

HOPS was utilized to forecast and investigate the synoptic circulation and transports in the Eastern Ligurian Sea. Results are described by Wang et al (2006) and in another manuscript in preparation.

IMPACT/APPLICATIONS

Better understanding and modeling of physical and interdisciplinary regional ocean dynamics are essential to multiple applications, including efficient real-time at-sea research experiments, naval operations and coastal seas management. Mathematical and computational methods and systems are necessary to predict and study ocean dynamics. Scientific progress occurs from the comparison and optimal combination of measurements and models via data assimilation. Interdisciplinary linkages include the traditional ocean sciences and atmospheric sciences, but also new relationships with other research disciplines within the framework of complex system earth sciences and engineering.

TRANSITIONS

Results are passed to the HU 6.1 research (N000140210989). Methods, software and data sets were transitioned to other research groups, several of which were involved in MURI-ASAP, AWACS and PLUSNet. They include: MIT-OE, Princeton U., WHOI, NATO Undersea Research Centre (NURC), NRL-Stennis, NPS, OASIS Inc., OGS-Trieste (Italy), CNR-Ancona (Italy), Brown U., Cal. Tech, U. of Frankfurt (Germany).

RELATED PROJECTS

Collaborations occurred with the HOPS team, including: ''Dynamics of Oceanic Motions, N000140210989''. This project enabled contributions to MURI-ASAP (N00014-04-1-0534), AWACS (N00014-05-1-0370) and PLUSNet. Specific interactions also occurred with several other groups. For physical-acoustical studies, this included Scripps (B. Cornuelle). For data assimilation, adaptive sampling and adaptive modeling, this involved: MIT-OE/EAPS (N. Patrikalakis, H. Schmidt, C. Evangelinos), NURC (E. Coelho and M. Rixen) and U. Mass (A. Gangopadhyay). For physical-biogeochemical studies, collaborations involved J. McCarthy (HU) and for Mediterranean studies, NURC, U. Ancono (N. Russo) and U. Trieste (G. Cosarini, C. Solidoro).

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Figures, presentations and other publications are available from: www.deas.harvard.edu/~pierrel. Other specific figures are available upon request.